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NATURE OF THE INFLUENCE OF MOISTENING OF COHESIVE SOILS WITH SALT SOLUTIONS ON SOIL COMPACTION

(On the example of loess-like loams)

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Explained is the effect of salinization of cohesive soils under mechanical loads. The compaction is shown to depend materially on the strength of the coagulation structure. The basic factors affecting the strength of the coagulation structure are as follows: the content of clay minerals and their crystal and chemical type, the composition of exchangeable ions in soils, and the hydrophylic nature of the base surfaces of clay minerals.

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THE NATURE OF THE INFLUENCE OF MOISTENING OF COHESIVE SOILS WITH SALT SOLUTIONS ON SOIL COMPACTION (ON THE EXAMPLE OF LOESS-LIKE LOAMS

Moscow IZVESTIYA VSESOYUZNOGO NAUCHNO-ISSLEDOVATEL'SKOGO INSTITUTA GIDROTEKHNIKI in Russian No 106, 1974 pp 287-296 manuscript received 28 Feb 74

[Article by Candidate of Technical Sciences B. F. Rel'tov and engineer A. N. Yermolayeva]

[Text] Investigations of changes of the strength and deformational properties of artificially salinized cohesive soils as a function of the salt concentration and composition have been conducted by many investigators [1-6].

The conducted investigations show that the character and quantity of changes of those properties depend essentially on both the genetic type of soils, their granulometric, chemical and mineralogical compositions (in particular, the mineralogical composition of the clayey fractions, exchange capacity and the composition of the exchange cations) and the concentration and composition of the salts introduced into soils during artificial salinization.

In spite of all the value of the revealed dependences, however, the conducted investigations do not give a clear concept of the mechanism of influence of artificial salinization on the indicated properties, without which a scientifically substantiated forecast is impossible in each specific case of possible changes of the structural properties of salinized soils.

Moreover, in connection with the wide use at the present time of artificial salinization of soils in order to prevent freezing of soils during the erection of earthen hydraulic engineering structures in the winter period, and in the long term also as an independent method of improving the structural properties of soils, a persistent need is arising for the development of scientifically substantiated recommendations on the application of artificial salinization of soils. Fundamental for that must be investigations directed toward revealing the mechanism of influence of artificial salinization on the structural properties of cohesive soils.

Only a limited task is set in the present work, that of clarifying on the basis of contemporary physicochemical concepts the mechanism of influence of moistening with salt solutions on soil compaction under the effect of mechanical loads.

To simplify the formulated problem one has in mind soils containing in the natural state a small amount of water-soluble salts and organic substances*. Among such soils, in particular, are the loessial soils of some regions of Central Asia (for example, the light loess-like loams of the Langarskoye deposit in the region of construction of the Nurekskaya hydrosystem, Tadzhik SSR). Laboratory and field tests conducted by us on the artificial salinization of those loams showed that as a result of salinization their deformational and strength properties change substantially [7-12].

To explain the mechanism of influence of salinization on compaction, of interest are some characteristic results of laboratory experiments conducted by us which reveal the interconnection between the compaction and structural strength of artificially salinized loams.

The compaction and structural strength were investigated as a function of the moisture content of samples of loam moistened with concentrated solutions of sodium chloride and calcium chloride.

1. Characteristics of the Investigated Soil

The principal physical properties and chemical and mineralogical composition of the Langarskiy loess-like loam are characterized by the following data.

Table 1 Granulometric and microaggregate compositions

Вид анализа	Удельный вес твердых частиц, $г/см^3$	Процентное содержание фракций диаметром, мм					
		>0,25	0,25–0,10	0,10–0,05	0,05–0,01	0,01–0,005	<0,005
Гранулометрический с добавкой пептизатора	2,71	0,1	0,1	12,2	52,6	16,4	18,6
Микроагрегатный . .	2,71	0,4	0,6	8,9	36,4	42,4	11,0

Key: A - Type of analysis B - Specific gravity of solid particles, g/cm^3
C - Percentage content of fractions with a diameter, in mm, of
1 - Granulometric with addition of peptizing agent 2 - Microaggregate

Characteristic properties: maximal hygroscopicity -- 4.5%; yield limit -- 27.6%; expansion limit -- 18.5%; plasticity number -- 9.1%. The principal rock-forming minerals of the clayey fractions of the Langarskiy loam are kaolinite and hydromica. In the composition of the exchange complex of the loam a predominant part (about 80%) consists of calcium and magnesium cations. The results of chemical analysis of aqueous extracts are presented in Table 1.

*The presence in soils of a considerable amount of water-soluble salts and organic substances makes it difficult to discover the principal mechanism of influence of additionally introduced salts on the properties of salinized soils.

The obtained data showed that the Langarskiy loess-like loam has a low content of water-soluble salts; its salinization has a carbonate-sulfate-chloride character.

Table 2

	Cl'	HCO_3'	SO_4''	Σa	$Ca^{\cdot\cdot} + Mg^{\cdot\cdot}$	$K^{\cdot} + Na^{\cdot}$	Σk	Σkal
мг/100 г	3,2	63,4	3,8	70,4	20,3	2,0	22,3	92,7
мг-экв	0,09	1,04	0,08	1,21	0,0[illegible]	1,21	1,21	2,42

Key: a - mg/100 g   b - mg-equiv

Obtained as a result of analysis of hydrochloric acid extracts were: insoluble residue -- 66.5; R_2O_3 -- 6.49; SO_3 -- 0.04; CaO + MgO -- 13.26 (in mg/100 g). Standard conversion into salts showed contents of 0.7% of calcium and magnesium sulfates in the loam and 24.0% of calcium and magnesium carbonates.

As is evident from Table 1, in the Langarskiy loess-like loam a considerable portion of the clay particles (with a diameter smaller than 0.005 mm), that is, the most active fractions, is in an aggregated state and forms microaggregates with enter mainly the composition of the dusty fractions (0.05 - 0.005 mm). Those microaggregates are water-resistant but are destroyed as a result of treatment with peptizing agent (4% solution of sodium pyrophosphate) in the process of preparation of the soil for granulometric analysis.

The deactivating effect of the pyrophosphate is caused by irreversible replacement of the exchange calcium and magnesium cations by sodium cations in the active centers on the surface of the clayey minerals comprising the microaggregates. As a result of that the hydrophilicity of the surface of those minerals increases and under conditions of free access of water to them during mixing the intra-aggregate coagulation bonds existing in the microaggregates are weakened to the point of complete decomposition of the microaggregates into the primary particles comprising them.

Irreversibility of the exchange reactions is caused by the bonding of calcium and magnesium cations which have gone into solution in the form of phosphoric acid salts difficultly soluble in water. Thus favorable conditions are created for very complete and irreversible replacement of exchange calcium and magnesium cations by sodium and, consequently, deaggregatization (peptization).

Increase of the content of clay particles as a result of treatment of the soil with sodium pyrophosphate (in granulometric analysis) in comparison with the untreated (in microaggregate analysis), illustrated in Table 1, testifies that in the composition of the Langarskiy loam there are microaggregates of a coagulation type which include particles of clayey minerals saturated in a predominant quantity by exchange calcium and magnesium. Such microaggregates are resistant to water but are destroyed when exchange processes arise [13-14].

In the composition of the soil under consideration there can also be micro-aggregates and even larger aggregates of other types, including types not water-resistant, with intra-aggregate bonds formed as a result of crystallization of readily soluble salts, or caused by the effect of capillary (meniscus) forces [13-14], and also non-water-resistant aggregates of a coagulation type [15]. In carbonate soils favorable conditions also are created for the formation of high-strength aggregates of a crystallization type, practically indestructible in water, caused by cementation of particles by calcium and magnesium carbonates and silicon compounds.

During artificial salination of carbonate soils with aqueous solutions of neutral salts (for example, sodium chloride) the strength of the crystallization bonds in aggregates of the cementation type can diminish somewhat through a certain increase of the solubility of carbonates.

Salinization of those groups exerts a very great effect on water-resistant coagulation intra-aggregate and inter-aggregate bonds, as a result of the possibility of the development of exchange reactions. The character and intensity of that effect depend on the concentration and composition of the moistening solution, and also on the degree of moistening of the soil.

2. Investigations of the Compaction of Langarskiy Loam

The compaction of Langarskiy loam was investigated in a standard compaction instrument (by the Proktor method) in the range of moisture contents of 12 to 19%. The soil was moistened by mixing air-dried powder with water or solutions. Soil moistened with distilled water, 1.5N (8.7%) sodium chloride solution and 1N (5.6%) calcium chloride solution was compacted*.

Presented on Figure 1 are dependences of the density on the moisture of loam when it is moistened with the indicated solutions and water. It is evident from the diagram that the greatest density of the skeleton, equal to 1.98 g/cm^3, is achieved during moistening with 1.5N sodium chloride solution. The optimal moisture content is 13.6%. The lowest density of the skeleton of the soil, equal to 1.78 g/cm^3, occurs when soil is treated with 1N calcium chloride solution. The optimal moisture content in that case is 16.6%. An intermediate position is occupied by the curve characterizing the dependence of the density on the moisture content of the loam moistened with distilled water. The maximal density in that case is 1.92 g/cm^3 and the optimal moisture content is 15.0%.

The obtained results show that soil moistened with sodium chloride solution has the greatest compaction. In that case the value of the optimal moisture content, at which the greatest density is achieved, has a very small value in comparison with moistening with pure water and calcium chloride solution.

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*It was established by previous investigations that the given concentrations are optimal for Langarskiy loam, as further increase of the concentration already has little influence on compaction.

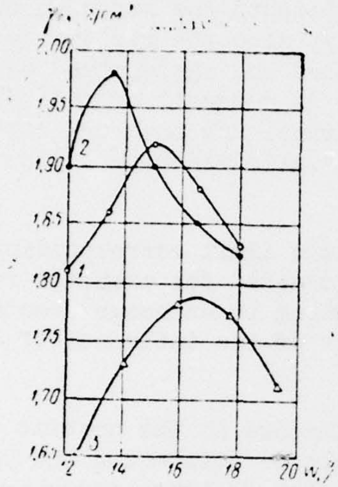

Figure 1. Dependence of the density γ_{sk}, g/cm^3 on the moisture content W of Nurekskiy loam: 1 - moistened with distilled water; 2 - the same with 1.5N sodium chloride solution; 3 - the same with 1N calcium chloride solution.
a - γ_{sk}, g/cm^3

On the contrary, very low compaction and correspondingly large moisture content occur when the soil is salinized with calcium chloride solution.

These results are explained by the different character of the exchange reactions in soils salinized with sodium chloride and calcium chloride.

In the first case the composition of the exchange complex as a result of the exchange reactions changes in the direction of increase of exchange sodium through the displacement of a certain amount of exchange calcium and magnesium, and in the second, through reduction of the sodium and potassium content and corresponding increase of the exchange calcium. As already mentioned above, replacement of exchange calcium and magnesium by sodium increases the hydrophilicity of the clayey minerals in aggregates, and this leads to disaggregation under conditions of free access of water.

In the given case, at a limited amount of moisture of the soil and a high concentration of interstitial solution the exchange reactions proceed far from completely, as a result of the small degree of dissociation of the exchange cations [16-19] or, in other words, the poor development of the ion-hydrate layer, and in addition has a reversible character, since the displaced calcium cations remain in the interstitial solution and do not form difficultly soluble compounds, as occurs, for example, in the case of treatment of the soil with sodium pyrophosphate solution.

Therefore it can be assumed that under those conditions the exchange reactions cause, not disaggregation but only some weakening of the intra-aggregate and interaggregate, water-resistant coagulation bonds through change of the mutual disposition of the particles at close distances corresponding to "close coagulation" at the primary minimum of the potential curve [19].

As a result of the weakening of those structural bonds (besides the weakening caused by the destruction of bonds not water-resistant) the strength of the structure of the soil decreases and, consequently, also the resistance of the structural elements of the soil (separate particles and aggregates) mutually displaced under the effect of mechanical loads. As a result of that the compaction improves when the moisture constant is optimal and the work expended on mechanical compaction of the soil artificially salinized with sodium chloride solution diminishes.

When the moisture content is increased to a certain limit corresponding to the optimal quantity, more favorable conditions are created for exchange reactions, since the number of cations capable of participating in exchange reactions increases, as a result of which the effectiveness of the influence of salinization on soil compaction increases.

The opposite processes occur when there is an increase in the content of exchange calcium in the exchange complex as a result of moistening the soil with calcium chloride solution. In that case the calcium cations, carrying a larger charge than the sodium and potassium cations, replace the latter more energetically. In that case favorable conditions are created for the formation of additional water-resistant coagulation bonds which strengthen the structures of the soil -- increase of resistance to the mutual displacement of aggregates under the effect of loads. Therefore the compaction of soil salinated with calcium chloride solution is worsened in comparison with unsalinized soil, and the work expended on its compaction at an optimal moisture content increases.

The influence of moistening soils with salt solutions on the structural strength is confirmed by the experimental investigations described below.

3. Investigations of the Strength of Soil Structures

The strength of the structure of soils was estimated by the value of the plastic strength P_m, determined with the conical plastometer of P. A. Rebinder [21,22]. The term "plastic strength of the structure" was proposed by P. A. Rebinder and characterizes the limiting value of shear stress, greater than that which causes plastic flow. The essence of that method consists in measuring the kinetics of the loading of a cone in the given system under the influence of constant load.

As has been shown by experimental investigations conducted for various disperse colloidal systems [21-25], the plastic strength characterizes the strength of the structure -- the unique carrying capacity of the given structurized system. The value of the plastic strength P_m is constant, that is, does not depend on the cone angle, in a wide range of soil moisture content values.

This method is widely used in the comparative estimation of the strength of dispersed structures formed by clays when treated with various reagents [19, 20, 23-25].

We investigated samples of Langarskiy loam in the range of moisture contents from 22.5 to 39.5%. The values of the plastic strength at low moisture contents are not presented in view of the considerable scattering of the experimental points, caused by lumpiness of the soil. The soils were moistened with distilled water and the above-indicated solutions.

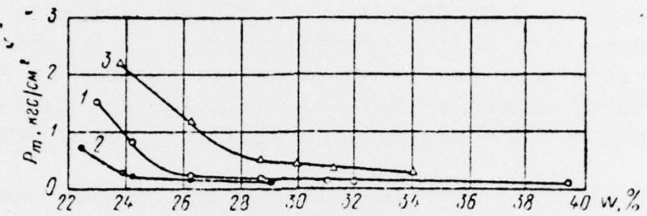

Figure 2. Dependence of the plastic strength P_m on the moisture content W of Langarskiy loam. 1 - moistening with distilled water; 2 - the same with 1.5N sodium chloride solution; 3 - the same with 1N calcium chloride solution. a - P_m, kg(force)/cm^2

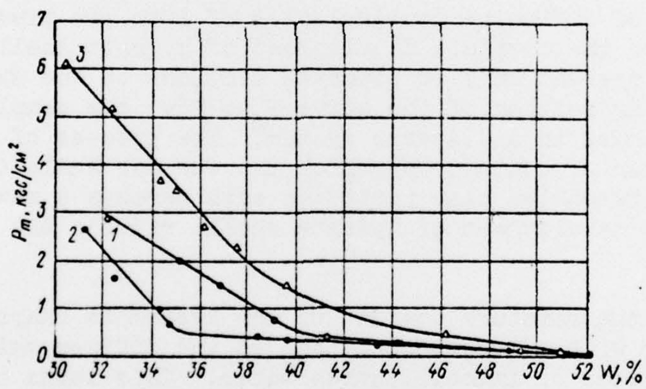

Figure 3. Dependences of the plastic strength P_m on the moisture content W of Krasnopavlovskiy loam.
Key: 1,2,3 and a as for Figure 2.

The results of investigations for Langarskiy loam are presented on Figure 2. As is evident from the diagram, the curve of the dependence of the strength on the moisture content during moistening of the soil with calcium chloride solution is higher (curve 3) than in the case of moistening with distilled water (curve 1). This indicates strengthening of the structure of the loam during salinizing with calcium chloride. Salinizing of the soil with sodium chloride solution reduces the strength of the soil structure (curve 2 lies below curve 1).

To illustrate the influence of the content of clay particles ($d < 0.005$ mm) presented on Figure 3 are curves of the dependence of the plastic strength P_m on the moisture content, obtained for samples of Krasnopavlovskiy heavy loess-like loam moistened with distilled water and the same solutions as in the experiments with the Langarskiy loam.

The Krasnopavlovskiy loam differs from the Langarskiy mainly in a larger content of clay particles ($d < 0.005$ mm) of 31.9% (according to data of a mechanical analysis made with sodium pyrophosphate). A considerable portion (about 40%) of those particles are in an aggregate state. In addition, the composition of the clayey minerals includes kaolinite and hydromica with mixed layers of montmorillonite. The clayey minerals are poorly crystallized.

The data presented on Figure 3 show that in comparison with the Langarskiy loam the plastic strength of the heavier Krasnopavlovskiy loam is more sensitive to change of the moisture content when not in the water-saturated state, and the influence of salinizing is more sharply manifested. The curves of the dependence of the plastic strength on the moisture content (Figures 2 and 3) can be approximated by two rectilinear sections which have different inclinations toward the axis of moisture.

Investigations conducted for different types of clays [23] showed that in the first section water of diffusive double layers of ions are present in a quantity insufficient for the complete development of hydrate shells. Immobilization water can be present only in separate sections of the system. In approaching the limiting section of the curve $P_m = f(w)$ the complete development of hydrate shells occurs in a disperse system. The process of dispersion is completed. The number of contacts on which the van der Waals forces of molecular interaction between the clay particles acts reaches a maximum value. At the same time the development of hydrate shells reduces the strength of the contacts.

Further increase of the moisture content of the system is characterized by the appearance, together with adsorptionally bonded and diffuse moisture, also of considerable quantitites of immobilization water. This leads to a sharp weakening of the molecular forces of interaction between the particles and the system gradually changes into a dilute suspension and loses tenacity.

The moisture content at the critical point is close to the Atterberg yield limit. Thus, for example, for Langarskiy loam W_T = 27.6% and the moisture content at the critical point is 26-28%. For Krasnopavlovskiy loam the yield points have the following values: 40.5% during moistening with water, 35.0% with sodium chloride solution and 41.0% with calcium chloride solution. Thus when the soil is moistened with sodium chloride solution the moisture content of the yield point decreases, and when moistened with calcium chloride, on the contrary, it increases in comparison with pure water. It is evident from the diagram that the effectiveness of salinizing decreases in proportion to approach of the moisture content to the yield point, and at moisture contents larger than the yield limit, the influence of salinizing is negligibly small.

The presented results indicate a substantial dependence not only of the compaction but also of the plastic properties on the strength of the soil structure. By acting on the structural strength by artificial salinization of the soils with salt solutions of different composition it is possible to control those properties in the desired direction.

The effectiveness of such a method of acting on the properties of soils depends mainly on the content of particles of clayey minerals in them, the degree and character of their aggregation and the crystal chemical type and composition of the exchange complex.

To illustrate the effectiveness of the physicochemical method of improving compaction, some results of field investigations of the compaction of salinized Langarskiy loess-like loam in experimental embankments through rolling in layers with a PVK-70e compactor, conducted by us in 1965-1967 at the construction site of the Nurekskaya dam, are presented [11,12]. The salinization was accomplished by moistening loam in the pit with 1.5N sodium chloride solution (87.5 kg of salt per cubic meter of solution)* in the course of 10 days. A uniformly salinized 10-meter bed of soil was thus obtained, at a moisture content close to the optimal. Rock salt to make the solution was added from a deposit situated 2.5 kilometers from the pit and outcropping on the day surface. Presented on Figures 4 and 5 are diagrams of the change of the density of the skeleton with depth in the thickness of the compacted layer of 55 cm (in the unconsolidated mass) of salinized soil in experimental embankments after compaction by 4 to 8 passes of the compactor (respectively). In both embankments the compaction was carried out at the optimal moisture content. It is evident from the diagrams that the salinized soil is compacted far more uniformly than the nonsalinized and even after four passes the density of the skeleton is at least 1.7 g/cm^3, whereas the unsalinized soil, even after eight passes of the compactor has a minimal density of the skeleton of 1.6 g/cm^3 (at the bottom of the layer).

The results of investigation of the compressive properties of loam showed that at initial moisture contents of the order of 15-17% and a density of 1.7 g/cm^3 the maximal increase of the deposition of salinized soil under the effect of a vertical load of 50 kg(force)/cm^2 does not exceed 5% in comparison with the unsalinized soil.

The parameters of the shearing strength of the soil after consolidation under the effect of a vertical load of 3 kg(force)/cm^2 were: for unsalinized soil $\phi = 24^\circ 05'$ and c = 0.3 kg(force)/cm2, and for the salinized soil $\phi = 29^\circ 45'$ and c = 0.25 kg(force)/cm2. The observed increase in the shearing strength of consolidated samples of soil salinized with sodium chloride solution is explained, evidently, by the greater density of the salinized soil (γ_{sk} = 1.72 g/cm^3) than of the unsalinized (γ_{sk} = 1.70 g/cm2).

*On the basis of laboratory experiments on the compaction of loam it has been established that the indicated concentration is optimal for the given soil. In that case the salt expenditure is 27 kg per cubic meter of soil.

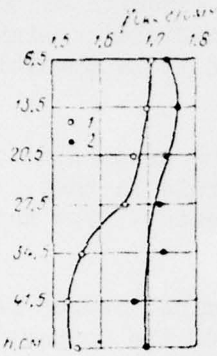

Figure 4. Change of the density of the skeleton with depth in experimental embankments of salinized and unsalinized Langarskiy loess-like loam after four passes of the PVK-70e compactor. 1 - unsalinized soil; 2 - salinized soil r, passes of the PVK-70e compactor, h = 55 cm and W = 16.0%. a - γ_{sk}, g/cm^3

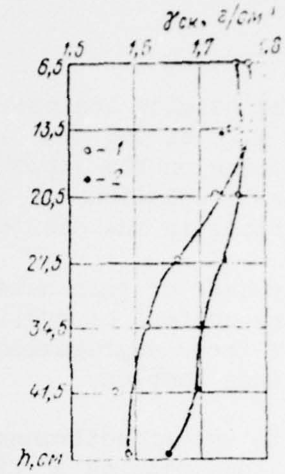

Figure 5. Change of the density of the skeleton with depth in experimental embankments of salinized and unsalinized Langarskiy loess-like loam after eight passes of the PVK-70e compactor. 1 - salinized soil; 2 - unsalinized soil. a - γ_{sk}, g/ cm^3

The method of improving the compaction of soils by artificial salinization can be used with considerable economic effect on objects located near rock salt deposits. In that case the desalinizing liquid can be prepared by underground leaching in bed of rock salt [26]. Approximate economic calculations made with respect to conditions of construction of the Nurekskaya dam showed that the post of compacting one cubic meter of salinized soil is 8.7 kopecks (with consideration of additional expenditures on salinization of 0.6 kopecks per cubic meter of soil), and of unsalinized soil is 26 kopecks. Reduction of the cost of compaction of salinized soil is explained by achievement of the required soil density with a smaller number of passes of the compactor and a greater thickness of the compacted layer.

Conclusions

1. It was established that the compaction of cohesive soils depends substantially on the strength of the coagulation structural bonds. Through physicochemical effect (during treatment with solutions of salts of different composition) on the strength of those bonds it is possible to directively regulate the compaction of cohesive soils.

2. The effectiveness of the physicochemical method of effect on the properties of cohesive soils depends on the content of particles of clayey minerals in them, their crystal chemical type, the composition of the exchange complex and the degree of aggregation caused by the presence of water-resistant coagulation bonds.

3. It was shown that the artificial salinization of loess-like loams with concentrated sodium chloride solution weakens the strength of the soil structure. As a result of that the compaction is worsened and the moisture content of the yield limit is reduced. In that case the shearing strength of the compacted soil is greater than that of the unsalinized.

4. An opposite effect is exerted by salinization with concentrated calcium chloride solution, as a result of which the soil structure is strengthened and its compaction worsens, and the moisture content of the yield limit increases.

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